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Distributed Sensor Network With Collective Computation For Situational Awareness°

Jared S. Dreicer*, Anders M. Jorgensen+, and Eric E. Dors#

* *Space Data Systems Group, NIS-3, Los Alamos National Laboratory*
+ *Space Instrumentation and System Engineering Group, NIS-4, Los Alamos National Laboratory*
# *Space and Atmospheric Sciences Group, NIS-1, Los Alamos National Laboratory*

Abstract. Initiated under Laboratory Directed R&D funding we have engaged in empirical studies, theory development, and initial hardware development for a ground-based Distributed Sensor Network with Collective Computation (DSN-CC). A DSN-CC is a network that uses node-to-node communication and on-board processing to achieve gains in response time, power usage, communication bandwidth, detection resolution, and robustness. DSN-CCs are applicable to both military and civilian problems where massive amounts of data gathered over a large area must be processed to yield timely conclusions. We have built prototype hardware DSN-CC nodes. Each node has self-contained power and is 6"x10"x2". Each node contains a battery pack with power feed from a solar panel that forms the lid, a central processing board, a GPS card, and radio card. Further system properties will be discussed, as will scenarios in which the system might be used to counter Nuclear/Biological/Chemical (NBC) threats of unconventional warfare. Mid-year in FY02 this DSN-CC research project received funding from the Office of Nonproliferation Research and Engineering (NA-22), NNSA to support nuclear proliferation technology development.

INTRODUCTION

Sensors play an important role in many of the nation's security programs and may be critical in the future for counter-terrorism and homeland defense missions. Applications include monitoring the movement of personnel or materials and environmental changes (air, water, or soil) at critical facilities, cities, international borders, or geographic regions. Indications and warnings of events can assist greatly in operational planning and response, and can enhance protection against nuclear, biological, or chemical (NBC) threats.

Ubiquitous *in-situ* computing and sensing devices are inevitable. They may soon exist in large numbers embedded everywhere in civilian systems and are of interest in current military, non-proliferation and other national security programs. Research and development is progressing in the area of sensor hardware technology and miniaturization so that that thousands or even millions may be deployed affordably. This will enable a revolutionary change in remote sensing capability. The traditional approaches to ground-based surveillance are largely inadequate for homeland

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protection from NBC threats since the initial detection of potential threats must be automated. Further, the automated surveillance systems to be developed must be unattended, cheap, compact, reliable, fault tolerant, and consume minimal power. Such systems will need to be fielded across a range of foreign and domestic locations.

This paper discusses the Distributed Sensor Network with Collective Computation (DSN-CC) research project that is developing an *in-situ* sensing and processing capability. Such a capability can support a layered defense and provide real-time alarms. This new DSN-CC technology uses communication among sensors to enable adaptive information collection and signal-processing capabilities. We believe DSN-CC may play an important role in the automated detection and tracking of proliferation or terrorism threats.

DISTRIBUTED SENSOR NETWORK WITH COLLECTIVE COMPUTATION

A DSN-CC is a network of smart sensor nodes that communicate with neighboring nodes in order to cooperatively solve a sensing problem. Devices capable of sensing, computing, communicating and possibly actuating will be widely available in the near future. Hardware research is ongoing to develop powerful and inexpensive devices that can serve as nodes in a DSN-CC, but the fundamental understanding of the DSN-CC has not been developed [1-4]. Science and technology challenges include organizing networks, inter-communicating, and using distributed computation to achieve the goals of collective behavior, autonomy, and adaptability. A system composed of hundreds to thousands of such devices may be used for surveillance and monitoring applications. As extremely large networks of such sensors begin to communicate, we enter a new realm of collective behavior with unexplored dynamics that can be harnessed. Such networks will be similar to biological systems in their robustness, reliability and adaptability.

In a DSN-CC individual devices will interact strongly on a local scale, sharing data and computation, and adapting to a changing environment on a local and global scale. Collective behavior can reduce an otherwise massive data-collection effort by allowing conclusion, rather than data, to be disseminated. In a DSN-CC raw data is distributed only locally, and conclusions are arrived at by negotiation among sensors. This eliminates the need for a central processing station, which is significant. Better and more efficient signature isolation can be achieved when neighbor sensors share data (“compare notes”). Single point of failure and expensive long-range communication are eliminated.

Not only does DSN-CC represent significant gains over traditional sensor arrays, recent results open up the opportunity for new applications that were heretofore impossible because of massive communications and central processing requirements. Straightforward gains are available in real-time event detection and classification, robustness to failure exhibited by coherent k-out-of-n systems, efficiency due to decreased resource requirements, decreased false alarms, and reduced possibilities of deception. However, the greatest gains will only be realized as we learn to build new systems that were previously impossible to achieve with conventional sensor arrays.

An example application for a DSN-CC is local event detection in a geographic area illustrated in Figure 1. Sensor nodes near the event exchange measurements and negotiate a concise conclusion, which is rapidly propagated across the network. This is but one simple example of a DSN-CC, and tremendous gains are realized over classical sensor arrays.

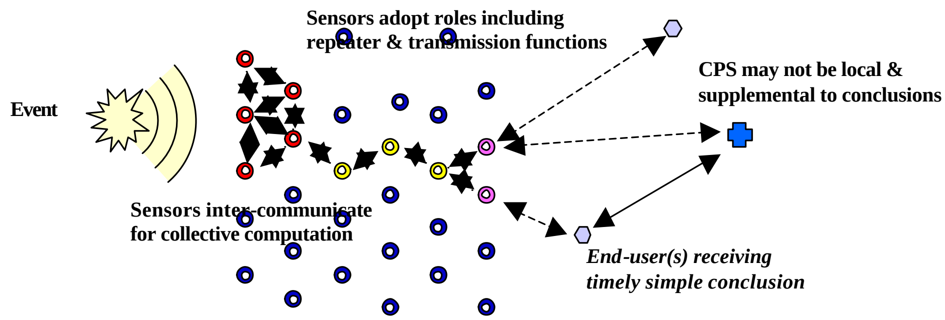


Figure 1. DSN-CC nodes detect a local event and communicate with near neighbor nodes.

Figure 2 shows three DSN-CC prototype nodes, each measures 6"x10"x2". The right side of Figure 2 shows the internals, from left to right, the battery pack with power feed from the solar panel that forms the lid, the central processing unit (CPU) top with global positioning system (GPS) card below, and radio (RF transmission) card. The sensor (not shown) is connected to the CPU board. These nodes have been used with acoustic sensors to determine the location and time of a sound impulse by exchanging data about the time of arrival of the impulse at each node.

Figure 2. Three prototype DSN-CC nodes and the internal hardware components.

DSN-CC Theory, Simulation, and Results

Classical sensor array technology utilizes a central processing station, designed using the star topology. This is a networking scheme in which data from a number of independent sensors are transmitted directly to a central processor (the hub of the star), where they are processed, combined, and delivered. The individual sensors do not directly communicate with each other. The conclusions are then redistributed to users. There are several problems with this approach. Transmitting the raw data long distances requires large amounts of power and bandwidth, or large amounts of time.

Central processing incurs delays and leaves the system vulnerable to single point failures. In contrast, DSN-CCs operate with short-range transmissions between neighbor nodes only and *in-situ* data processing. This approach eliminates single point failures, provides redundancy, saves bandwidth, and delivers conclusions rapidly to users. With large numbers of sensors the star-topology paradigm breaks down.

DSN-CC Theory

There are significant scaling problems associated with the classical star-topology [3]. The classical star-topology is successful for arrays with small dimensions and few sensors, but for networks with a large number of sensors it is likely to fail for several reasons. First, for limited bandwidth and growing numbers of sensors, N, the time it takes for all sensors to transmit grows linearly with N. This decreases the sampling rate, a problem for time-critical applications. Secondly, transmitter power scales as the square of the transmission distance, so long-range communications are very expensive. In a classical sensor array where all information is transmitted to a hub, the energy one sensor needs to transmit increases as N (for an array with constant separation between sensors the transmission distance increases as $N^{1/2}$, thus the energy one sensor needs to expend on a transmission scales as N). The energy needed to extract data from all N sensors grows as N^2. A sensor can only transmit with a duty cycle of 1/N, so the time-averaged energy consumption of a sensor is independent of array size.

By contrast, we have found that significant savings are possible with an approach in which neighbor communication takes place. Suppose information still propagates to a hub, which is some sensor in the network. Information is passed from sensor to sensor and merged with a sensor's own information before it is passed on. In that case the time to extract will be a small constant times $N^{1/2}$ (scales as N in the classical case). Each sensor transmits once with energy independent of the size of the network, so total energy scales as N (scales as N^2 in the classical) [3]. Clearly, in simple applications where DSN-CC is used to merely improve the speed and efficiency of information transmission, there are significant quantitative gains over classical sensor arrays. For a DSN-CC peak power is independent of the size of the network. For the classical case the sensor must be designed for peak power operation, which is dependent on the size of the array.

DSN-CC Simulation

Simulations of randomly generated sensor networks with different numbers of sensors in them were performed. The simulation model was based on a sensor that includes communications inputs from neighboring sensors, local measurements, output, and a state machine. This architecture was used to demonstrate cooperative data analysis and detection. The simulation model contained sources and sensors. The sources emitted an omni-directional beacon, and the sensors could measure only the direction to the source if it was within detection range. The sensors communicated only with neighbors that were within transmission range. In order to compute the source locations, the sensors need to exchange measurements. The goal was to have the source locations computed and to have that information distributed across the network. Details are reported in [3].

DSN-CC Results

Simulations were run for networks of 100 sensors to 20000 sensors. One node in the network was monitored as a proxy for when detection information had been transmitted across the network. The simulations were performed to determine the energy and time for detection information to be sent across the network to the exfiltration[1] node, and how energy and time scale as a function of network size (number of sensors). Results were compared to the classical array approach of having each sensor in turn transmit information to a central hub (exfiltration node) where information is processed.

The left graph in Figure 3 shows the exfiltration energy as a function of the network size. Total exfiltration energy is the transmission energy used from the time the sources first appear until the time when the exfiltration node knows the position of all sources. The total exfiltration energy in the classical case is shown in the top curve, which scales with the square of the number of sensors (N^2). Exfiltration energy for the DSN-CC case is shown in the bottom curve, which scales as the number of sensors to the 3/2 power. This means that the total exfiltration energy per sensor scales as number of sensors to the 1/2 power. So the total amount of energy expended per sensor grows with network size, N. However, this energy is expended over a time interval that also grows with the square root of the number of sensors. The plot reflects total exfiltration energy divided by total exfiltration time and the total number of sensors to obtain the average exfiltration energy per time step per sensor. For the DSN-CC case the energy expended per sensor per time step is independent of the size of the network, N.

[1] Exfiltration node is a proxy for the central hub in the classical case to which detection information has been transmitted from across the network to facilitate comparison of time and energy.

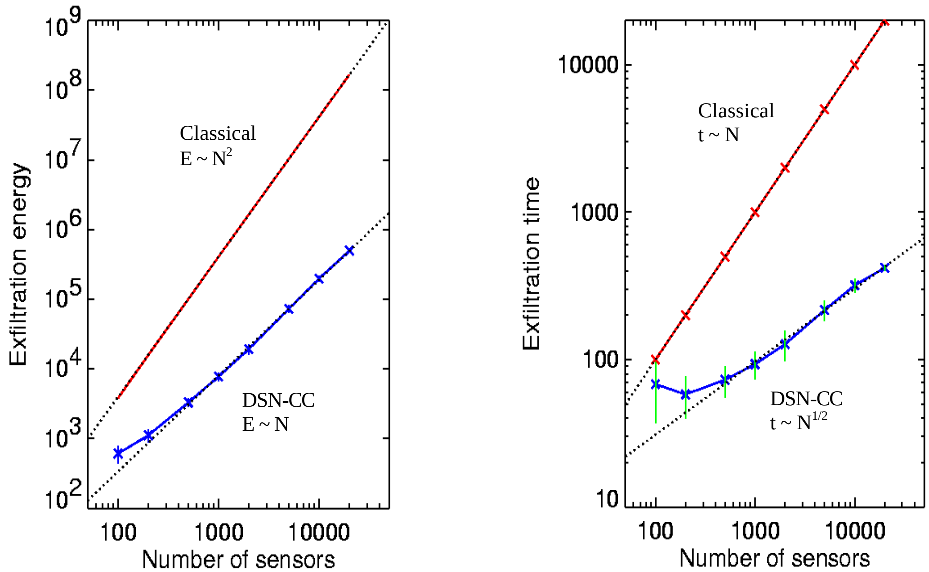


Figure 3. Simulation results for total exfiltration energy (left) and time (right) as a function of number of sensors in the classical case top and the DSN-CC case bottom. Dashed lines are the theoretically expected best exfiltration energy and time for the classical and DSN-CC cases.

The right graph in Figure 3 shows the exfiltration time as a function of the network size. Exfiltration time is the time it takes from when the sources first appear until the exfiltration node knows the position of all the sources. Exfiltration time in the classical case, in which every sensor has to report directly to a central hub, is shown in the top curve. The exfiltration time scales linearly with the number of sensors (N). Exfiltration time for the DSN-CC case is shown in the bottom curve. The points are the median exfiltration time and the vertical bars are the RMS distribution of exfiltration times around that value. For large network sizes the exfiltration scales as $N^{1/2}$. For small network sizes the exfiltration time appears to increase and the spread around the median increases. For small network sizes the trend of a larger exfiltration time than that suggested by the scaling is being investigated.

RADIATION DETECTION SITUATIONAL AWARENESS

DSN-CC capabilities provide the technical underpinnings to address national security missions. Applications include situational awareness, monitoring, or defense of critical facilities or geographic regions (homeland defense and proliferation detection). DSN-CCs also support a military configured in mobile, fast-striking forces to execute missions ranging from peacekeeping to conflict (special operations and counter terrorism). Sensor suites depend on the application, but may include anything from miniaturized *in-situ* sensors to remote sensors on robots, UAVs, aircraft, or satellites. Many signatures can be detected only by placing sensors in close proximity to the target. These include vibrations in the earth, short-range radio and acoustic signals, production facility effluents, spores from biological weapons, and radiation from nuclear material. These signatures can be vital to identifying and understanding mobile targets and hard targets such as underground production facilities. However a number of basic research and development issues must be resolved to successfully field *in-situ* DSN-CCs for specific applications. In particular, radiation detection situational awareness will require continued development of DSN-CC capabilities and nuclear detector technology. Both are research areas that LANL is actively investigating.

DSN-CCs are pertinent to radiation detection situational awareness for the following applications: the protection of critical facilities, cities, or regions; the search and diagnoses of nuclear material in wide area radiation surveys; the response to nuclear accidents or terrorist acts requiring monitoring for dispersal of radioactivity; safeguards for the protection of nuclear material in storage; and finally, remote sensing addressing space exploration and planetary science questions.

The physical signatures of interest for nuclear material are known. The difficulty of the problem varies depending on the specific radiation detection application. Each application has specific problem requirements and boundary conditions that significantly impact the complexity of the problem. For example, the requirements for detection may vary with respect to the intensity and mobility of the signatures, the topography, population density, and proximity of physical structures in the detection area, and the number of dispersal or transit pathways.

Radiation Detection Challenges and DSN-CC Concept

There are two primary radiation detection challenges that must be addressed. Nuclear sensors have short ranges since the signals are small and the backgrounds are large. The solution to these challenges is to either reject the large background signal by imaging or to bring the detector to the source. Bringing the sensor closer to the source via DSN-CC is the concept proposed. This is achieved by utilizing a hybrid DSN-CC that employs both statically placed and mobile detectors over a large area (application dependent).

The DSN-CC provides a generic approach to different applications of this problem. Depending on the application, the physical configuration of static deployment of the DSN-CC can provide dense 0-dimensional (point), 1-dimensional (line, e.g. along a roadway), 2-dimensional (field, e.g. geographic region) and even 3-dimensional (e.g. at different altitudes within the atmosphere) measurements, which can be monitored over time. Thus, the DSN-CC concept for radiation detection situational awareness is the integration of mobility (ground or air based detector systems). An illustration of the hybrid DSN-CC system is presented in Figure 4.

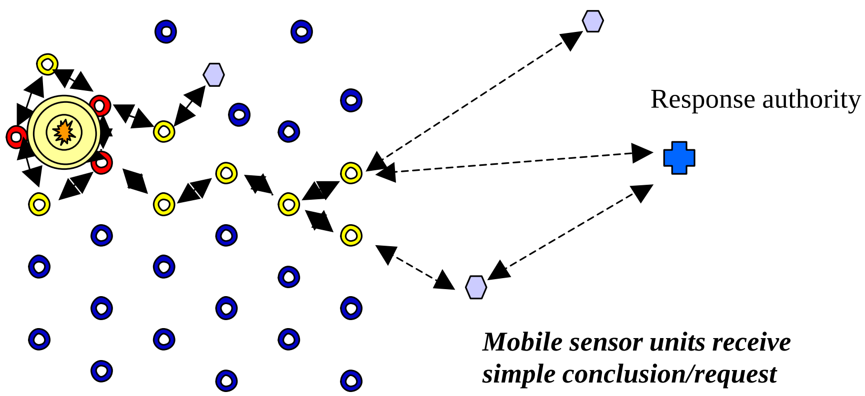


Figure 4. Concept for radiation detection situational awareness utilizes a hybrid DSN-CC approach composed of static nodes that cue mobile nodes (waiting or moving randomly).

The mobile detectors may be stationary units (waiting to be requested) or randomly moving units (that can be called to a location). Since the background signal varies over a geographic area, mobile detector backgrounds will vary, which causes a problem when trying to distinguish the natural variations from that caused by a real target. The DSN-CC can resolve the unknown background for a mobile detector by transmitting the "calibrated" or local background from the nearest static detector in real-time. An alternative approach is to characterize the geophysical and manmade backgrounds and their variations in a geographic region and correlate the data to the detector position as it moves.

The hybrid DSN-CC concept relies on deploying enough static and randomly moving radiation detectors so that one is in the right place at the time a target passes. Each detector must be large enough to have a reasonable neutron or gamma detection efficiency. But the system may be effective because of the large number of detectors and not necessarily because of the detector performance. The network density can be increased by orders of magnitude to realize a large sensitivity gain, if the cost of the detectors is inexpensive enough.

DSN-CC with neutron or gamma ray detectors will be crucial to future radiation detection scenarios. Hundreds of thousands of sensors may have to work unattended over large areas in a harsh environment over many years. Ruggedness, simplicity, low power consumption, and low manufacturing and maintenance costs are critical. A brief description of two detector development efforts that address a number of these requirements and that may provide appropriate detection technology in the future is presented.

The first project is a gamma detector technology research and development effort investigating a cadmium zinc tellurium (CdZnTe) device supported by NA-22, NNSA. CdZnTe is a new compound semiconductor that is being developed for gamma ray spectroscopy. Since the resistivity of the material is high, it is ideally suited for gamma ray spectroscopy at room temperature. LANL is leading the development of this new technology in several areas including: research on device physics and electronic properties; and development of specialized detector probes, electronics, and spectrum analysis software [5]. Figure 5 provides a picture of CdZnTe gamma device.

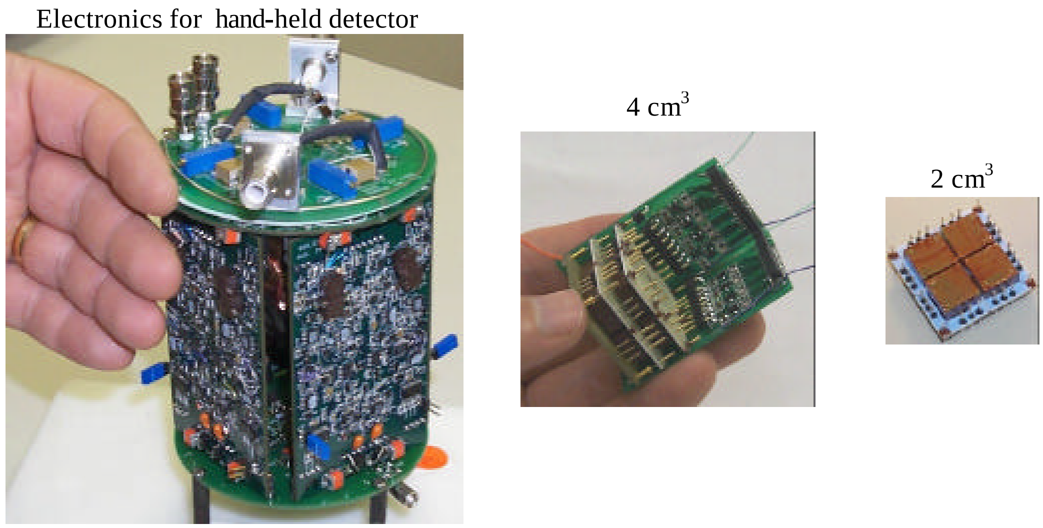
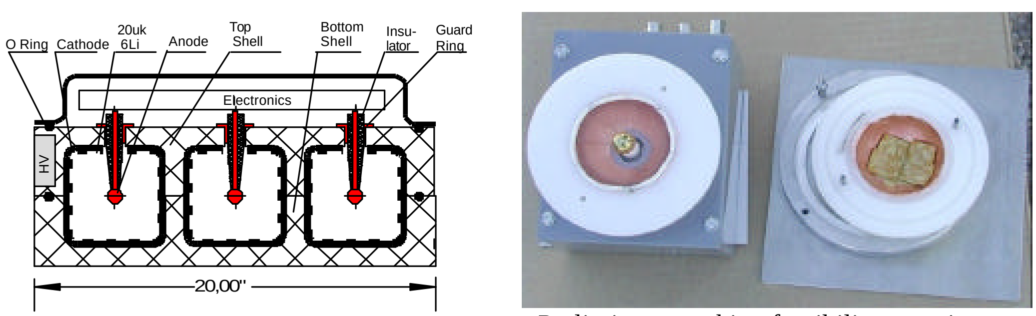


Figure 5. Gamma ray detector based on CdZnTe compound semiconductor material.

The second project is a neutron detector technology research and development effort that is investigating a ^{6}Li ionization chamber. The concept is an inexpensive and robust neutron detector that can be easily mass-produced. It is based upon a pulse mode ionization chamber lined with ^{6}Li as an active substance. Preliminary calculations show a relative neutron intrinsic efficiency of about 5% per cell. The gas purity is not critical for the detector's operation, which dramatically reduces the cost. The appropriate fill gas (Ar, N, Xe, air) can be selected for the specific application. Figure 6 is a cross section of the design and a picture of a preliminary ^{6}Li device. Results from an early feasibility experiment demonstrated a charge collection efficiency over 90% indicating a beneficial signal to noise ratio [6].



Slab cross-section.

Preliminary working feasibility experiment using a 2" diameter spherical detector 5"X5".

Figure 6. Neutron detector concept based on ^{6}Li pulse mode ionization chamber.

CONCLUSION

DSN-CC's may provide tremendous gains over classical sensor arrays. DSN-CC's operate with short-range transmissions only and *in-situ* data processing. This approach eliminates single point failures, provides redundancy, saves communication bandwidth, and rapidly delivers conclusions to users. For typical situation assessment problems, response time and energy consumption scales as $N^{1/2}$, and N for a DSN-CC of N nodes, a significant improvement over scaling of N, and N^2 for a classical array of N nodes. DSN-CC is a **revolutionary expansion** in sensing capability, **not** a limited incremental increase over existing capabilities. The DSN-CC radiation detection situational awareness concept employs static and mobile detectors. Such a system increases coverage, sensitivity gain, and provides a deterrent value. However, a better understanding of the technical decisions and trade off between cost, simplicity, detection efficiency, and network density is required. The required detector efficiency must be determined within the constraints of the application and system design using the lowest-cost, -power, and smallest size.

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